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**APPARATUS TO POSITION A
MICROELECTROMECHANICAL PLATFORM**

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Apparatus to Position a Microelectromechanical Platform

STATEMENT OF GOVERNMENT INTEREST

This invention was made with Government support under contract no.
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Sandia Corporation. The Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

The present invention relates to microelectromechanical (MEM)
positioning devices, and more particularly to a MEM positioning device that
10 comprises parallelogram linkages to achieve substantially translational motion of
a platform (i.e., motion in a single plane and without rotation).

Precise control of position and orientation is required for many types of
MEM device applications. An example of an application benefiting from such
precise micropositioning is high-performance optical MEM laser scanner as
15 disclosed by J.R. Wendt *et al.*, *J. Vac. Sci. Technol. B* 18, 3608 (2000). In this
laser scanner, a diffractive optical element is patterned on a polysilicon shuttle
that is linearly translated in the plane of a substrate, thereby enabling scanning of
an output laser beam. To maintain proper orientation of the diffractive optical
element relative to the laser beam to be scanned, the shuttle must exhibit
20 substantially translational motion. For the scanner disclosed by Wendt *et al.*,
linear translation was accomplished by a gear-driven rack, or by a reciprocating
arm linked to a rotating gear. Other micropositioning MEM devices have been
proposed to independently control the orthogonal movement of a stage in two
dimensions (e.g., U.S. Pat. No. 5,962,949 to Dhuler). However, there remains a
25 need for reliable, precise micropositioning of a platform in two orthogonal
dimensions wherein orientation of the platform is maintained over a range of
motion and rubbing surfaces are eliminated.

SUMMARY OF THE INVENTION

The present invention provides a MEM positioner, comprising a substrate, a moveable platform, and at least one linkage mechanism having a plurality of links, wherein the linkage mechanism is pivotably attached to the substrate by at least two anchor links and pivotably attached to the moveable platform by at least two platform links, and whereby the platform is constrained to exhibit substantially translational movement in a plane. The linkage mechanisms can be parallelogram linkages.

The MEM positioner can be actuated by a variety of means, including electrostatic, electromagnetic, piezoelectric, and thermal activation of the linkage mechanisms and/or the platform. Rotary actuation of one or more of the anchor links enables fixed location actuators and precise translational control of the platform position. Such actuation can be provided by rotary electrostatic actuators operatively connected to one or more of the anchor links.

The MEM positioner can be fabricated by a variety of device fabrication technologies generally known to those in the art, including sacrificial surface micromachining, bulk micromachining, and LIGA (LIGA is a German acronym that stands for lithography, electroplating, and molding). The MEM positioner can be formed on a silicon substrate by surface micromachining, using planar fabrication process steps known to the integrated circuit (IC) art. The platform can be formed of polycrystalline or single crystal silicon and can have a structure and properties modified for specialized applications, such as optical applications.

Advantages of the MEM positioner of the present invention include precision positioning of a moveable platform; no wear-induced change in performance, due to the absence of rubbing surfaces; inherent orientation stability due to the constrained system geometry; and extremely low hysteresis.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and form part of the specification, illustrate the present invention and, together with the description, explain the invention. In the drawings, like elements are referred to by like numbers.

Figure 1 shows a four-bar linkage to illustrate substantially translational motion.

Figure 2 shows a top view of a MEM positioner. Fig. 2A shows a linkage mechanism having parallelogram linkages to achieve substantially translational motion of a platform. Fig. 2B shows the linkage mechanism with a pair of bidirectional rotary electrostatic actuators to actuate the anchor links of the linkage mechanism.

Figure 3 shows a top view of a two-mechanism MEM positioner, comprising two orthogonal linkage mechanisms configured to achieve controlled translational motion of a platform. Fig. 3A shows the two-mechanism MEM positioner in an as-fabricated position. Fig. 3B shows the two-mechanism MEM positioner in a displaced position.

Figure 4 shows a top view of a four-mechanism MEM positioner. Fig. 4A shows the four-mechanism MEM positioner in an as-fabricated position. Fig. 4B shows the four-mechanism MEM positioner in a displaced position.

DETAILED DESCRIPTION OF THE INVENTION

Linkages are mechanisms comprising a plurality of interconnected links to provide constrained kinematic motion. That is, movement of one of the links will cause the remaining links to move to prescribed, predictable positions. Linkages can be designed to produce various combinations of translational and rotational motion of a platform (i.e., a stage). Linkages are particularly useful for MEM device applications because they enable controlled motion of a suspended platform in a plane without requiring rolling or sliding motions that can cause wear and early device failure.

One of the simplest and most useful linkages is the four-bar linkage **100**, shown in Fig. 1. The four-bar linkage **100** comprises a plurality of moveable links denoted as a crank link **101**, a coupler link **102**, and a rocker link **103**. The crank link **101** and the rocker link **103** are each anchored to a stationary substrate by a pivoting joint **105** thereby defining a fixed link **104**. The crank link **101** and rocker link **103** are each attached at the other end thereof to the coupler link **102** by a pivoting joint **106**. Depending on the relative length of the links, the various moveable links **101**, **102**, **103** can exhibit different types of motions relative to the fixed link **104**. If the linkage **100** forms a parallelogram, such that the crank and rocker links **101**, **103**, respectively, are of equal length and the coupler link **102** is equal in length to the fixed link **104**, then the coupler link **102** will be constrained to move parallel to the fixed link **104**. In this case, the coupler link **102** will exhibit substantially translational motion relative to the fixed link **104** with a single degree of freedom.

According to the present invention, substantially translational motion can be used to move a MEM platform that must be constrained to move in a plane while maintaining a parallel condition relative to the underlying substrate. Figure 2A schematically illustrates a first example of a MEM positioner **10** having a linkage mechanism **20** according to the present invention for achieving substantially translational motion of a MEM platform **21**. The linkage mechanism **20** comprises two parallelogram linkages **22**, **23** interconnected by a moveable frame **24**. The moveable frame **24** can be a right-angle frame or can be any angle, so long as the linkages **22**, **23** are parallelograms.

The anchor linkage **22** can have anchor links **25** of equal length, each anchor link **25** having a first end pivotably attached to the substrate **26** at fixed anchor pivots **28**. The anchor pivots **28** can be flexible to torque applied in the plane of the substrate **26** and can be rigid to resist out-of-plane motions. The anchor pivots **28** can be pin joints, flexural hinges, or any joint type that provide pivoting motion of the anchor links **25**. For example, flexural hinges resisting out-of-plane motion can be made by making the width of the link at the joint much less than its height. The opposite ends of the anchor links **25** can be likewise

pivotably attached to the moveable frame **24** at frame pivots to form a coupler link. The anchor pivots **28** can be spaced at the same distance as the frame pivots. The anchor pivots **28** thereby define a fixed link having a length equal to the coupler link defined by the frame pivots. A four-bar parallelogram linkage is thereby formed, wherein the opposing links are of equal length. A platform linkage **23** can be similarly formed with a pair of platform links **27** connecting the platform **21** to the frame **24** with a flexible or rotatable attachment at platform and frame pivots. The platform pivots and frame pivots can be spaced equidistant, thereby forming a parallelogram platform linkage **23**.

Because of the parallelogram geometry of the anchor linkage **22**, the orientation of the frame **24** is constrained to remain parallel to anchor pivots **28** during movement. Similarly, because of the parallelogram geometry of the platform linkage **23**, the platform **21** is constrained to maintain a parallel orientation to the right angle portion of frame **24** to which it is connected. Consequently, the platform **21** is constrained to move relative to the anchor pivots **28** without rotation. The platform **21** therefore exhibits substantially translational motion.

A variety of actuation means known to those skilled in the art, such as electrostatic, electromagnetic, piezoelectric, and thermal actuation, can be used to actuate the positioner **10**. Translation of the moveable platform **21** in this example of the present invention can be achieved by any means whereby at least one actuator is operatively connected to the linkages **22**, **23**, the frame **24**, or the platform **21**. Regardless of the actuation means, the platform **21** is constrained to exhibit substantially translational motion without rotation due to the parallelogram linkages **22**, **23**.

Figure 2B shows a convenient means for actuating the linkage mechanism **20** comprising rotary actuation of the anchor links **25** about the anchor pivots **28**. Rotary actuation enables the use of fixed location actuators to provide precise translational control of the platform **21** position. Rotary actuation can be achieved using rotary electrostatic actuators comprising electrostatic comb drives providing motion about an arc. A unidirectional rotary electrostatic actuator,

comprising a stationary electrostatic arm and a moveable electrostatic arm oriented at an angle to each other, is disclosed in U.S. Patent 6,211,599 to Barnes *et al.*, which is incorporated herein by reference.

Fig. 2B shows an example of rotary actuation of the anchor links **25** of anchor linkage by means of bidirectional rotary electrostatic actuators **30** to control the positioning of the platform **21**. Each bidirectional rotary electrostatic actuator **30** comprises a plurality of arcuate electrostatic fingers extending outward from the sides of the anchor links **25** to form a moveable electrostatic comb **31**. A pair of stationary electrostatic combs **32** are located about the moveable electrostatic comb **31** with fingers of the stationary electrostatic combs **32** being interdigitated with the fingers of the moveable electrostatic comb **31**. The individual fingers can be arcuate and can have a length that increases with distance away from the anchor pivots **28**. The moveable electrostatic comb **31** is generally electrically grounded. The fingers of the moveable electrostatic comb **31** are urged into engagement with the interdigitated fingers of one or the other of the stationary electrostatic combs **32** in response to a voltage (e.g., 20-100 volts) applied to one of the stationary electrostatic combs **32** of each bidirectional rotary electrostatic actuator **30**. Electrical connections can be made to the rotary electrostatic actuators **30** by contact pads **33** and wiring **34**. The rotary electrostatic actuators **30** in Fig. 2B can be operated in tandem. The actuated anchor links **25** are thereby caused to move about the anchor pivots **28**, causing the frame **24** to move in a path while maintaining substantially parallel orientation to the anchor pivots **28**.

Other actuation means known to the art can also be used to vary the actuation force applied to the linkage mechanism **20**. For example, a unidirectional electrostatic actuator fixed as in Fig. 2 but with only one stationary electrostatic comb **32** can be operatively connected to each anchor link **25** to provide motion thereto. The anchor links **25** can each have a spring (not shown) to restore the linkage mechanism **20** when the applied voltage is removed. Each electrostatic actuator **30** can further include one or more stops to prevent contact between the moveable and stationary electrostatic combs **31**, **32** that could

otherwise result in electrical short-circuiting. Furthermore, in some embodiments of the present invention, only one of the anchor links **25** need be activated, with the electrostatic combs **31**, **32** of the other anchor link **25** being used to capacitively sense the position of the platform **21**.

5 Activation of the anchor linkage **22** only, with the platform linkage **23** unactivated, will move the platform **21** with one degree of freedom in an arc about the anchor pivots **28** while maintaining its angular orientation. A pair of linkage mechanisms **20** can be oriented orthogonal to each other and connected to the platform **21** to provide two degrees of freedom. A second example of the
10 MEM positioner **10** of the present invention comprising two linkage mechanisms **20** is shown in Figs. 3A and 3B. Fig. 3A shows a MEM positioner **10**, comprising two linkage mechanisms **20** and the platform **21**, in the as-fabricated position. The two-mechanism positioner **10** can provide independent X-Y motion of the platform **21** in a plane parallel to the substrate **26**, as indicated by the activated
15 positioner **10** in Fig. 3B. As described above, activation of the positioner **10** can be achieved by activation of each of the linkage mechanisms **20**, the platform **21**, or the frame **24**.

As shown by a third example of the present invention in Figure 4,
20 additional linkage mechanisms **20** can be added to further control the range of motion of the platform **21** and to achieve greater stability thereof. Fig. 4A shows an as-fabricated position of a four-mechanism MEM positioner **10**. Fig. 4B shows a displaced position of the platform **21** after actuation of the various linkage mechanisms **20** of the four-mechanism positioner **10**. The presence of the additional linkage mechanisms **20** can provide greater out-of-plane stiffness
25 and can provide greater orientational stability. Two degrees of freedom of translational motion can be achieved by actuating any two of the four linkage mechanisms **20** shown in Figs. 4A and 4B. Actuation of additional linkage mechanisms **20** to deliver additional force to the positioner **10** can result in an increased rate at which the position of the platform **21** can be changed.

30 The platform **21** can be controlled to provide motion through any desired path, or through paths in orthogonal directions, by an open-loop controller or

other control means. For example, the platform **21** can be controlled to scan in a linear direction and step in a direction perpendicular to the scanning direction, while maintaining orientation relative to the substrate **26**. The range of motion can be determined by the range of motion of the pivoting joints, the length of the anchor links, and the length of the platform links. The range of motion can span distances that are as short as sub-micron to over 100 microns.

The two-dimensional motion of the platform **21** can exhibit multiple natural resonant frequencies and resonant modes that depend on parameters of the positioner **10** such as stiffness of pivoting joints, component geometries, and component masses. These resonances can be employed to achieve periodic motion of the platform **21**. Periodic motion can be desirable for a variety of specialized applications, such as optical scanners.

For specialized applications, such as optics, the structure and properties of the platform **21** can be modified to alter the properties of electromagnetic radiation impinging thereon. Optical elements, such as a diffractive optical element, can be formed on or attached to the platform **21**. The platform **21** can comprise single crystal silicon to improve the optical properties (e.g., by using a silicon-on-insulator substrate).

The MEM positioner **10** can be fabricated by a variety of MEM device fabrication technologies generally known to those in the art, including sacrificial surface micromachining, bulk micromachining, and LIGA (e.g., *Fundamentals of Microfabrication* by Marc Madou, CRC Press (1997); and U.S. Patent 6,082,208 to Rodgers *et al.*, which are incorporated herein by reference).

Surface micromachining can be used to fabricate the MEM positioner **10** using planar fabrication process steps known to those in the IC industry. The entire MEM positioner **10**, including the actuation system, can be fabricated from a single mechanical level of polysilicon. It can also be fabricated from multiple levels of polysilicon. It is generally advantageous to create the structure to provide maximum vertical, or out of plane, stiffness. This is generally accomplished by using as many structural levels as are available for the elements of the structure where out of plane compliance can exist.

A silicon substrate **26** can be used for supporting the MEM positioner **10**. Surface micromachining processes are based on repeated steps of depositing and photolithographically patterning a plurality of alternating layers of low-stress polysilicon (also termed polysilicon) and a sacrificial material (e.g., silicon dioxide or a silicate glass) to build up the structure of the MEM positioner **10** layer by layer on the silicon substrate **26**. Vias etched through the sacrificial layers at predetermined locations provide anchor points to the substrate and for mechanical and electrical interconnections between the various polysilicon layers. Functional elements of the MEM positioner **10** are built up layer by layer using a series of deposition and patterning steps. Typical in-plane lateral dimensions of the functional elements can range from one micron to several hundred microns or more, while individual layer thickness is typically about 1-3 microns. After the structure of the MEM positioner **10** is built up, it can be released for movement by removing the sacrificial material in part or entirely by exposure to a selective etchant comprising hydrofluoric acid (HF) in liquid or vapor form which does not substantially attack the polysilicon layers while etching away the sacrificial material. The released structure generally consists of a first layer of polysilicon that provides electrical interconnections (i.e., wiring) and/or a voltage reference plane (e.g., a ground plane) and up to three or more layers of mechanical polysilicon that can be stacked and interconnected to form the linkages **20**, platform **21**, and electrostatic actuators **30**. The position of the platform **21** can be maintained during processing (including the release etch and post processing), by the inclusion of fuses (e.g. comprising polysilicon bridges) that hold the structure in place and can be removed by electrically blowing the fuses with an applied voltage to release the platform for movement. Alternatively, one or more removable constraining clips can also be used to secure the platform **21** during fabrication. Because the entire process is based on standard IC fabrication technology, a large number of fully assembled MEM positioners **10** can be batch-fabricated on a silicon substrate without the need for piece-part assembly.

It will be understood that the above description is merely illustrative of the applications of the principles of the present invention, the scope of which is to be determined by the claims viewed in light of the specification. Other variants and modifications of the invention will be apparent to those of skill in the art.

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